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SCIENTIFIC MEMOIRS

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III.

RÖNTGEN RAYS

RÖNTGEN RAYS

MEMOIRS BY RÖNTGEN, STOKES
AND J. J. THOMSON

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W. P. I

PREFACE

THE new kind of radiation known as X-rays, or Röntgen rays, from the name of their discoverer, were first observed and studied by Professor W. C. Röntgen, of the University of Würzburg, in 1895, and the announcement of their discovery was made in a paper which appeared that year, and which is reprinted in this volume. As was noticed later these radiations had been previously detected and some of their properties noted by other observers, notably Professor Lenard; but it is to Röntgen that we owe the first systematic study of the methods of production and of the remarkable properties of these rays. Nearly all the general properties, both positive and negative, were investigated by Röntgen and carefully stated. These results are contained in the first three pages of this volume.

The most important experiments, however, and those which have led to the most important conclusions, were made by Professor J. J. Thomson, of Cambridge. They proved the fact that a dielectric traversed by these radiations became a conductor, or, in other words, was ionized. This discovery in the hands of Professor Thomson and his students has led to a series of most interesting and important researches, all bearing upon the intimate connection between matter and electricity.

Many hypotheses have been advanced to account for the peculiar properties of the X-rays. Röntgen himself at first was favorably inclined to the idea that they were waves due to longitudinal vibrations in the ether, but later he was convinced

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with transverse waves in the ether. There were grave obstacles, from many stand-points, to either of these theories, and the first suggestion which seemed to offer a satisfactory explanation of all the properties of the rays came when, instead of waves, the idea of pulses in the ether was introduced. This idea in its simplicity is that the cathode rays being negatively charged and travelling with great velocity, give rise to intensely sudden disturbances in the ether when their motions are stopped by reaching a solid obstacle. These disturbances are of the nature of irregular pulses, and their properties are quite different from those of regular trains of waves.

This idea of accounting for Röntgen rays by the theory of pulses occurred almost simultaneously to Sir George Gabriel Stokes, to Professor J. J. Thomson, and to Professor Lehmann, of Karlsruhe. Stokes's paper, in which he explains his theory, is reproduced in full in this volume, as are also the essential portions of Professor Thomson's article.

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ON A NEW KIND OF RAYS

BY

W. C. RÖNTGEN

TWO COMMUNICATIONS

Sitzungsberichte der Würzburger Physikalischen-Medicinischen Gesellschaft,
1895—Wiedemann, *Annalen der Physik und Chemie*, **64**, 1898

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ON A NEW KIND OF RAYS

BY

W. C. RÖNTGEN

FIRST COMMUNICATION

1. If the discharge of a fairly large induction-coil be made to pass through a Hittorf vacuum-tube, or through a Lenard tube, a Crookes tube, or other similar apparatus, which has been sufficiently exhausted, the tube being covered with thin, black card-board which fits it with tolerable closeness, and if the whole apparatus be placed in a completely darkened room, there is observed at each discharge a bright illumination of a paper screen covered with barium platino-cyanide, placed in the vicinity of the induction-coil, the fluorescence thus produced being entirely independent of the fact whether the coated or the plain surface is turned towards the discharge-tube. This fluorescence is visible even when the paper screen is at a distance of two metres from the apparatus.

It is easy to prove that the cause of the fluorescence proceeds from the discharge-apparatus, and not from any other point in the conducting circuit.

2. The most striking feature of this phenomenon is the fact that an active agent here passes through a black card-board envelope, which is opaque to the visible and the ultra-violet rays of the sun or of the electric arc; an agent, too, which has the power of producing active fluorescence. Hence we may first investigate the question whether other bodies also possess this property.

We soon discover that all bodies are transparent to this agent,

though in very different degrees. I proceed to give a few examples: Paper is very transparent; * behind a bound book of about one thousand pages I saw the fluorescent screen light up brightly, the printers' ink offering scarcely a noticeable hinderance. In the same way the fluorescence appeared behind a double pack of cards; a single card held between the apparatus and the screen being almost unnoticeable to the eye. A single sheet of tin-foil is also scarcely perceptible; it is only after several layers have been placed over one another that their shadow is distinctly seen on the screen. Thick blocks of wood are also transparent, pine boards two or three centimetres thick absorbing only slightly. A plate of aluminium about fifteen millimetres thick, though it enfeebled the action seriously, did not cause the fluorescence to disappear entirely. Sheets of hard rubber several centimetres thick still permit the rays to pass through them.† Glass plates of equal thickness behave quite differently, according as they contain lead (flint-glass) or not; the former are much less transparent than the latter. If the hand be held between the discharge-tube and the screen, the darker shadow of the bones is seen within the slightly dark shadow-image of the hand itself. Water, carbon disulphide, and various other liquids, when they are examined in mica vessels, seem also to be transparent. That hydrogen is to any considerable degree more transparent than air I have not been able to discover. Behind plates of copper, silver, lead, gold, and platinum the fluorescence may still be recognized, though only if the thickness of the plates is not too great. Platinum of a thickness of 0.2 millimetre is still transparent; the silver and copper plates may even be thicker. Lead of a thickness of 1.5 millimetres is practically opaque; and on account of this property this metal is frequently most

* By "transparency" of a body I denote the relative brightness of a fluorescent screen placed close behind the body, referred to the brightness which the screen shows under the same circumstances, though without the interposition of the body.

† For brevity's sake Lohmann uses the expression "fluorescent screen" instead of "fluorescent screen" which is the correct one.

useful. A rod of wood with a square cross-section (20×20 millimetres), one of whose sides is painted white with lead paint, behaves differently according as to how it is held between the apparatus and the screen. It is almost entirely without action when the X-rays pass through it parallel to the painted side; whereas the stick throws a dark shadow when the rays are made to traverse it perpendicular to the painted side. In a series similar to that of the metals themselves their salts can be arranged with reference to their transparency, either in the solid form or in solution.

3. The experimental results which have now been given, as well as others, lead to the conclusion that the transparency of different substances, assumed to be of equal thickness, is essentially conditioned upon their density: no other property makes itself felt like this, certainly to so high a degree.

The following experiments show, however, that the density is not the only cause acting. I have examined, with reference to their transparency, plates of glass, aluminium, calcite, and quartz, of nearly the same thickness; and while these substances are almost equal in density, yet it was quite evident that the calcite was sensibly less transparent than the other substances, which appeared almost exactly alike. No particularly strong fluorescence (see p. 6 below) of calcite, especially by comparison with glass, has been noticed.

4. All substances with increase in thickness become less transparent. In order to find a possible relation between transparency and thickness, I have made photographs (see p. 6 below) in which portions of the photographic plate were covered with layers of tin-foil, varying in the number of sheets superposed. Photometric measurements of these will be made when I am in possession of a suitable photometer.

5. Sheets of platinum, lead, zinc, and aluminium were rolled of such thickness that all appeared nearly equally transparent. The following table contains the absolute thickness of these sheets measured in millimetres, the relative thickness referred

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THICKNESS	RELATIVE THICKNESS	DENSITY
Pt 0.018 mm.	1	21.5
Pb 0.05 “	3	11.3
Zn 0.10 “	6	7.1
Al 3.5 “	200	2.6

We may conclude from these values that different metals possess transparencies which are by no means equal, even when the product of thickness and density are the same. The transparency increases much more rapidly than this product decreases.

6. The fluorescence of barium platino-cyanide is not the only recognizable effect of the X-rays. It should be mentioned that other bodies also fluoresce; such, for instance, as the phosphorescent calcium compounds, then uranium glass, ordinary glass, calcite, rock-salt, and so on.

Of special significance in many respects is the fact that photographic dry plates are sensitive to the X-rays. We are, therefore, in a condition to determine more definitely many phenomena, and so the more easily to avoid deception; wherever it has been possible, therefore, I have controlled, by means of photography, every important observation which I have made with the eye by means of the fluorescent screen.

In these experiments the property of the rays to pass almost unhindered through thin sheets of wood, paper, and tin-foil is most important. The photographic impressions can be obtained in a non-darkened room with the photographic plates either in the holders or wrapped up in paper. On the other hand, from this property it results as a consequence that undeveloped plates cannot be left for a long time in the neighborhood of the discharge-tube, if they are protected merely by the usual covering of pasteboard and paper.

It appears questionable, however, whether the chemical action on the silver salts of the photographic plates is directly caused by the X-rays. It is possible that this action proceeds from the fluorescence of the plates, which is excited by the X-rays.

in the glass plate itself or perhaps in the layer of gelatin. "Films" can be used just as well as glass plates.

I have not yet been able to prove experimentally that the X-rays are able also to produce a heating action; yet we may well assume that this effect is present, since the capability of the X-rays to be transformed is proved by means of the observed fluorescence phenomena. It is certain, therefore, that all the X-rays which fall upon a substance do not leave it again as such.

The retina of the eye is not sensitive to these rays. Even if the eye is brought close to the discharge-tube, it observes nothing, although, as experiment has proved, the mediæ contained in the eye must be sufficiently transparent to transmit the rays.

7. After I had recognized the transparency of various substances of relatively considerable thickness, I hastened to see how the X-rays behaved on passing through a prism, and to find whether they were thereby deviated or not.

Experiments with water and with carbon disulphide enclosed in mica prisms of about 30° refracting angle showed no deviation, either with the fluorescent screen or on the photographic plate. For purposes of comparison the deviation of rays of ordinary light under the same conditions was observed; and it was noted that in this case the deviated images fell on the plate about 10 or 20 millimetres distant from the direct image. By means of prisms made of hard rubber and of aluminium, also of about 30° refracting angle, I have obtained images on the photographic plate in which some small deviation may perhaps be recognized. However, the fact is quite uncertain; the deviation, if it does exist, being so small that in any case the refractive index of the X-rays in the substances named cannot be more than 1.05 at the most. With a fluorescent screen I was also unable to observe any deviation.

Up to the present time experiments with prisms of denser metals have given no definite results, owing to their feeble transparency and the consequently diminished intensity of the

With reference to the general conditions here involved on the one hand, and on the other to the importance of the question whether the X-rays can be refracted or not on passing from one medium into another, it is most fortunate that this subject may be investigated in still another way than with the aid of prisms. Finely divided bodies in sufficiently thick layers scatter the incident light and allow only a little of it to pass, owing to reflection and refraction; so that if powders are as transparent to X-rays as the same substances are in mass—equal amounts of material being presupposed—it follows at once that neither refraction nor regular reflection takes place to any sensible degree. Experiments were tried with finely powdered rock-salt, with fine electrolytic silver-powder, and with zinc-dust, such as is used in chemical investigations. In all these cases no difference was detected between the transparency of the powder and that of the substance in mass, either by observation with the fluorescent screen or with the photographic plate.

From what has now been said it is obvious that the X-rays cannot be concentrated by lenses; neither a large lens of hard rubber nor a glass lens having any influence upon them. The shadow-picture of a round rod is darker in the middle than at the edge; while the image of a tube which is filled with a substance more transparent than its own material is lighter at the middle than at the edge.

8. The question as to the reflection of the X-rays may be regarded as settled, by the experiments mentioned in the preceding paragraph, in favor of the view that no noticeable regular reflection of the rays takes place from any of the substances examined. Other experiments, which I here omit, lead to the same conclusion.

One observation in this connection should, however, be mentioned, as at first sight it seems to prove the opposite. I exposed to the X-rays a photographic plate which was protected from the light by black paper, and the glass side of which was turned towards the discharge-tube giving the X-rays. The

plates of platinum, lead, zinc, and aluminium arranged in the form of a star. On the developed negative it was seen plainly that the darkening under the platinum, the lead, and particularly the zinc, was stronger than under the other plates, the aluminium having exerted no action at all. It appears, therefore, that these three metals reflect the rays. Since, however, other explanations of the stronger darkening are conceivable, in a second experiment, in order to be sure, I placed between the sensitive film and the metal plates a piece of thin aluminium-foil, which is opaque to ultra-violet rays, but is very transparent to the X-rays. Since the same result substantially was again obtained, the reflection of X-rays from the metals above named is proved.

If we compare this fact with the observation already mentioned that powders are as transparent as coherent masses, and with the further fact that bodies with rough surfaces behave like polished bodies with reference to the passage of the X-rays, as shown also in the last experiment, we are led to the conclusion already stated that regular reflection does not take place, but that bodies behave towards the X-rays as turbid media do towards light.

Since, moreover, I could detect no evidence of refraction of these rays in passing from one medium into another, it would seem that X-rays move with the same velocity in all substances; and, further, that this speed is the same in the medium which is present everywhere in space and in which the particles of matter are imbedded. These particles hinder the propagation of the X-rays, the effect being greater, in general, the more dense the substance concerned.

9. Accordingly it might be possible that the arrangement of particles in the substance exercised an influence on its transparency; that, for instance, a piece of calcite might be transparent in different degrees for the same thickness, according as it is traversed in the direction of the axis, or at right angles to it. Experiments, however, on calcite and quartz gave a negative result.

from the results of his beautiful experiments on the transmission of the cathode rays of Hittorf through a thin sheet of aluminium, that these rays are phenomena of the ether, and that they diffuse themselves through all bodies. We can say the same of our rays.

In his most recent research, Lenard has determined the absorptive power of different substances for the cathode rays, and, among others, has measured it for air from atmospheric pressure to 4.10, 3.40, 3.10, referred to 1 centimetre, according to the rarefaction of the gas contained in the discharge-apparatus. Judging from the discharge-pressure as estimated from the sparking distance, I have had to do in my experiments for the most part with rarefactions of the same order of magnitude, and only rarely with less or greater ones. I have succeeded in comparing by means of the L. Weber photometer—I do not possess a better one—the intensities, taken in atmospheric air, of the fluorescence of my screen at two distances from the discharge-apparatus—about 100 and 200 millimetres; and I have found from three experiments, which agree very well with each other, that the intensities vary inversely as the squares of the distances of the screen from the discharge-apparatus. Accordingly, air absorbs a far smaller fraction of the X-rays than of the cathode rays. This result is in entire agreement with the observation mentioned above, that it is still possible to detect the fluorescent light at a distance of 2 metres from the discharge-apparatus.

Other substances behave in general like air; they are more transparent to X-rays than to cathode rays.

11. A further difference, and a most important one, between the behavior of cathode rays and of X-rays lies in the fact that I have not succeeded, in spite of many attempts, in obtaining a deflection of the X-rays by a magnet, even in very intense fields.

The possibility of deflection by a magnet has, up to the present time, served as a characteristic property of the cathode rays; although it was observed by Hertz and Lenard that there

from each other by their production of phosphorescence, by the amount of their absorption, and by the extent of their deflection by a magnet." A considerable deflection, however, was noted in all of the cases investigated by them; so that I do not think that this characteristic will be given up except for stringent reasons.

12. According to experiments especially designed to test the question, it is certain that the spot on the wall of the discharge-tube which fluoresces the strongest is to be considered as the main centre from which the X-rays radiate in all directions. The X-rays proceed from that spot where, according to the data obtained by different investigators, the cathode rays strike the glass wall. If the cathode rays within the discharge-apparatus are deflected by means of a magnet, it is observed that the X-rays proceed from another spot—namely, from that which is the new terminus of the cathode rays.

For this reason, therefore, the X-rays, which it is impossible to deflect, cannot be cathode rays simply transmitted or reflected without change by the glass wall. The greater density of the gas outside of the discharge-tube certainly cannot account for the great difference in the deflection, according to Lenard.

I therefore reach the conclusion that the X-rays are not identical with the cathode rays, but that they are produced by the cathode rays at the glass wall of the discharge-apparatus.

13. This production does not take place in glass alone, but, as I have been able to observe in an apparatus closed by a plate of aluminium 2 millimetres thick, in this metal also. Other substances are to be examined later.

14. The justification for calling by the name "rays" the agent which proceeds from the wall of the discharge-apparatus I derive in part from the entirely regular formation of shadows, which are seen when more or less transparent bodies are brought between the apparatus and the fluorescent screen (or the photographic plate).

I have observed, and in part photographed, many shadow-

charm. I possess, for instance, photographs of the shadow of the profile of a door which separates the rooms in which, on one side, the discharge-apparatus was placed, on the other the photographic plate; the shadow of the bones of the hand; the shadow of a covered wire wrapped on a wooden spool; of a set of weights enclosed in a box; of a galvanometer in which the magnetic needle is entirely enclosed by metal; of a piece of metal whose lack of homogeneity becomes noticeable by means of the X-rays, etc.

Another conclusive proof of the rectilinear propagation of the X-rays is a pin-hole photograph which I was able to make of the discharge-apparatus while it was enveloped in black paper; the picture is weak but unmistakably correct.

15. I have tried in many ways to detect interference phenomena of the X-rays; but, unfortunately, without success, perhaps only because of their feeble intensity.

16. Experiments have been begun, but are not yet finished, to ascertain whether electrostatic forces affect the X-rays in any way.

17. In considering the question what are the X-rays—which, as we have seen, cannot be cathode rays—we may perhaps at first be led to think of them as ultra-violet light, owing to their active fluorescence and their chemical actions. But in so doing we find ourselves opposed by the most weighty considerations. If the X-rays are ultra-violet light, this light must have the following properties:

(a) On passing from air into water, carbon disulphide, aluminium, rock-salt, glass, zinc, etc., it suffers no noticeable refraction.

(b) By none of the bodies named can it be regularly reflected to any appreciable extent.

(c) It cannot be polarized by any of the ordinary methods.

(d) Its absorption is influenced by no other property of substances so much as by their density.

That is to say, we must assume that these ultra-violet rays behave entirely differently from the ultra-red, visible, and

I have been unable to come to this conclusion, and so have sought for another explanation.

There seems to exist some kind of relationship between the new rays and light rays; at least this is indicated by the formation of shadows, the fluorescence and the chemical action produced by them both. Now, we have known for a long time that there can be in the ether longitudinal vibrations besides the transverse light-vibrations; and, according to the views of different physicists, these vibrations must exist. Their existence, it is true, has not been proved up to the present, and consequently their properties have not been investigated by experiment.

Ought not, therefore, the new rays to be ascribed to longitudinal vibrations in the ether?

I must confess that in the course of the investigation I have become more and more confident of the correctness of this idea, and so, therefore, permit myself to announce this conjecture, although I am perfectly aware that the explanation given still needs further confirmation.

WÜRZBURG, Physikalisches Institut der Universität.

December, 1895.

SECOND COMMUNICATION

Since my work must be interrupted for several weeks, I take the opportunity of presenting in the following paper some new phenomena which I have observed.

18. It was known to me at the time of my first publication that X-rays can discharge electrified bodies; and I conjecture that in Lenard's experiments it was the X-rays, and not the cathode rays, which had passed unchanged through the aluminium window of his apparatus, which produced the action described by him upon electrified bodies at a distance. I have, however, delayed the publication of my experiments until I could contribute results which are free from criticism.

These results can be obtained only when the observations are

the electrostatic forces proceeding from the vacuum tube, from the conducting wires, from the induction apparatus, etc., but is also closed against air which comes from the neighborhood of the discharge-apparatus.

To secure these conditions I had a chamber made of zinc plates soldered together, which was large enough to contain myself and the necessary apparatus, which could be closed air-tight, and which was provided with an opening which could be closed by a zinc door. The wall opposite the door was for the most part covered with lead. At a place near the discharge-apparatus, which was set up outside the case, the zinc wall, together with the lining of sheet lead, was cut out for a width of 4 centimetres; and the opening was covered again air-tight with a thin sheet of aluminium. The X rays penetrated through this window into the observation space.

I observed the following phenomena:

(a) Electrified bodies in air, charged either positively or negatively, are discharged if X-rays fall upon them; and this process goes on the more rapidly the more intense the rays are. The intensity of the rays was estimated by their action on a fluorescent screen or a photographic plate.

It is immaterial in general whether the electrified bodies are conductors or insulators. Up to the present I have not found any specific difference in the behavior of different bodies with reference to the rate of discharge; nor as to the behavior of positive and negative electricity. Yet it is not impossible that small differences may exist.

(b) If the electrified conductor be surrounded not by air but by a solid insulator, *e. g.* paraffin, the radiation has the same action as would result from exposure of the insulating envelope to a flame connected to the earth.

(c) If this insulating envelope be surrounded by a close-fitting conductor which is connected to the earth, and which, like the insulator, is transparent to X rays, the radiation produces on the inner electrified conductor no action which can be detected by my apparatus.

(d) The observations noted under (a) and (b) are in accordance

air through which X-rays have passed possesses the power of discharging electrified bodies with which it comes in contact.

(c) If this is really the case, and if, further, the air retains this property for some time after it has been exposed to the X-rays, then it must be possible to discharge electrified bodies which have not been themselves exposed to the rays, by conducting to them air which has thus been exposed.

We may convince ourselves in various ways that this conclusion is correct. One method of experiment, although perhaps not the simplest, I shall describe.

I used a brass tube 3 centimetres wide and 45 centimetres long; at a distance of some centimetres from one end a part of the wall of the tube was cut away and replaced by a thin aluminium plate; at the other end, through an air-tight cap, a brass ball fastened to a metal rod was introduced into the tube in such a manner as to be insulated. Between the ball and the closed end of the tube there was soldered a side-tube which could be connected with an exhaust-apparatus; so that when this is in action the brass ball is subjected to a stream of air which on its way through the tube has passed by the aluminium window. The distance from the window to the ball was over 20 centimetres.

I arranged this tube inside the zinc chamber in such a position that the X-rays could enter through the aluminium window of the tube perpendicular to its axis. The insulated ball lay then in the shadow, out of the range of the action of these rays. The tube and the zinc case were connected by a conductor, the ball was joined to a Hankel electroscope.

It was now observed that a charge (either positive or negative) given to the ball was not influenced by the X-rays so long as the air remained at rest in the tube, but that the charge instantly decreased considerably if by exhaustion the air which had been subjected to the rays was drawn past the ball. If by means of storage cells the ball was maintained at a constant potential, and if the modified air was drawn continuously through the tube, an electric current arose just as if

the ball were connected to the wall of the tube by a poor conductor.

(f) The question arises, How does the air lose the property which is given it by the X-rays? It is not yet settled whether it loses this property gradually of itself—*i. e.*, without coming in contact with other bodies. On the other hand, it is certain that a brief contact with a body of large surface, which does not need to be electrified, can make the air inactive. For instance, if a thick enough stopper of wadding is pushed into the tube so far that the modified air must pass through it before it reaches the electrified ball, the charge on the ball remains unaffected even while the exhaustion is taking place.

If the wad is in front of the aluminium window, the result obtained is the same as it would be without the wad; a proof that it is not particles of dust which are the cause of the observed discharge.

Wire gratings act like wadding; but the gratings must be very fine, and many layers must be placed over each other if the modified air is to be inactive after it is drawn through them. If these gratings are not connected to the earth, as has been assumed, but are connected to a source of electricity at a constant potential, I have always observed exactly what I had expected; but these experiments are not yet completed.

(g) If the electrified bodies, instead of being in air, are placed in dry hydrogen, they are also discharged by the X-rays. The discharge in hydrogen seemed to me to proceed somewhat more slowly; yet this is still uncertain on account of the difficulty of obtaining exactly equal intensities of the X-rays in consecutive experiments.

The method of filling the apparatus with hydrogen precludes the possibility that the layer of air which was originally present, condensed on the surface of the bodies, played any important rôle.

(h) In spaces which are highly exhausted the discharge of a body by the direct incidence of X-rays proceeds much more

the same vessels when filled with air or hydrogen at atmospheric pressure.

(*i*) Experiments are about to be begun on the behavior of a mixture of chlorine and hydrogen under the influence of X-rays.

(*j*) In conclusion I would like to mention that the results of investigations on the discharging action of X-rays in which the influence of the surrounding gas is not taken into account should be received with great caution.

19. It is advantageous in many cases to include a Tesla apparatus (condenser and transformer) between the discharge-apparatus which furnishes the X-rays and the induction-coil. This arrangement has the following advantages: first, the discharge-apparatus is less easily penetrated and is less heated; second, the vacuum maintains itself for a longer time, at least in my self-constructed apparatus; third, many discharge-tubes under these conditions give more intense X-rays. With tubes which have not been exhausted sufficiently or have been exhausted too much to be driven satisfactorily by the induction-coil alone, the addition of the Tesla transformer renders good service.

The question immediately arises—and I allow myself to mention it without being able to contribute anything to its solution at present—whether X-rays can be produced by a continuous discharge under constant difference of potential; or whether variations of this potential are essential and necessary for the production of the rays.

20. In paragraph 13 of my first memoir I announced that X-rays could originate not only in glass, but in aluminium also. In the continuation of my experiments in this direction I have not found any solid body which cannot, under the action of the cathode rays, produce X-rays. There is also no reason known to me why liquids and gases may not behave in the same manner.

Quantitative differences in the behavior of different substances have appeared, however. If, for instance, the cathode rays

millimetre thick, the other half of aluminium 1 millimetre thick, we see on the photographic image of this double plate, taken by means of a pin-hole camera, that the platinum sends out many more X-rays from the side struck by the cathode rays (the front side) than does the aluminium from the same side. However, from the rear side the platinum emits practically no X-rays, while the aluminium sends out relatively many. These last rays are produced in the front layers of the aluminium and pass through the plate.

We can easily devise an explanation of this observation, yet it may be advisable to learn other properties of the X-rays before so doing.

It must be mentioned, however, that there is a practical importance in the facts observed. For the production of the most intense X-rays platinum is best suited, according to my experiments up to the present. I have used for some weeks with great success a discharge-apparatus in which the cathode is a concave mirror of aluminium, and the anode is a plate of platinum placed at the centre of curvature of the mirror and inclined to the axis of the mirror at an angle of 45° .

21. The X-rays proceed in this case from the anode. I must conclude, though, from experiments with apparatus of different kinds that it is entirely immaterial, so far as the intensity of the X-rays is concerned, whether the place where the rays are produced is the anode or not.

A discharge-apparatus was prepared specially for experiments with the alternating currents of the Tesla transformer; in it both electrodes were aluminium concave mirrors whose axes were at right angles; at their common centre of curvature there was placed a platinum plate to receive the cathode rays. Further information will be given later as to the usefulness of this apparatus.

Würzburg, Physikalisches Institut der Universität.

March 9, 1896.

FURTHER OBSERVATIONS ON THE PROPERTIES OF THE X-RAYS

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THIRD COMMUNICATION

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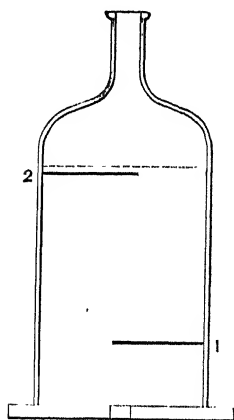
THIRD COMMUNICATION

1. If an opaque plate be placed between a discharge-apparatus* which is emitting intense X-rays and a fluorescent screen, in such a position that it shades the entire screen, there may still be noticed, in spite of the plate, an illumination of the barium platino-cyanide. This illumination can be seen even when the screen lies directly on the plate; and one is inclined at first sight to consider the plate as transparent. If, however, the screen lying on the plate be covered by a thick pane of glass, the fluorescent light becomes much weaker; and it vanishes entirely if, instead of using a glass plate, the screen is surrounded by a cylinder of sheet-lead 0.1 centimetre thick, which is closed at one end by the non-transparent plate, and at the other by the head of the observer.

The phenomenon now described may be due either to diffraction of rays of very great wave-length, or to the fact that the bodies which surround the discharge-apparatus and through which the rays pass, especially the air, themselves emit X-rays.

* All the discharge-tubes mentioned in the following communication are constructed according to the principle given in paragraph 20 of my second paper. The greater portion of them I obtained from the firm of Greiner & Friedrichs, in Stutzerbach i. Th., whom I wish to thank publicly for the material which has been furnished me in such abundance and without expense.

The latter explanation is the correct one, as may be proved with the following apparatus, among others: The figure represents a very thick-walled glass bell-jar, 20 centimetres high and 10 centimetres broad, which is closed by a thick zinc plate



cemented on. At 1 and 2 are inserted plates of lead in the shape of circular segments; these are somewhat larger than half the cross-section of the jar, and prevent the X-rays, which enter through an opening in the zinc plate covered with a celluloid film, from reaching directly the space above the lead plate, 2. On the upper side of this sheet of lead there is fastened a small barium platino-cyanide screen, which nearly fills the entire cross-section of the jar. This cannot be struck either by the direct rays or by such as have suffered a

single diffuse reflection at a solid body (*e. g.*, the glass wall). The jar is filled with dust-free air before each experiment. If X-rays are made to enter the jar in such a manner that they are all received upon the lead screen 1, no fluorescence is observed at 2; the fluorescent screen first begins to light up on the half not covered by the lead plate 2 only when by tipping the bell-jar direct radiation reaches the space between 1 and 2. If the bell-jar is now connected to an aspirator-pump worked by a stream of water, it is observed that the fluorescence becomes more and more weak as the exhaustion proceeds; but when the air is readmitted the intensity again increases.

Since now, as I have found, the mere contact with air which has been exposed shortly before to X-rays does not produce any sensible fluorescence of the barium platino-cyanide, we must conclude from the experiment described that air during its exposure to radiation emits X-rays in all directions.

If our eyes were as sensitive to X-rays as they are to light

like a light burning in a room moderately filled with tobacco smoke; perhaps the colors of the direct rays and of those coming from the particles of air might be different.

The question as to whether the rays emitted by a body which is receiving radiation are of the same kind as those which are incident, or, in other words, whether the cause of these rays is diffuse reflection or a process like fluorescence, I have not yet been able to decide. The fact that the rays coming from the air are photographically active can be proved easily; and this action makes itself noticeable sometimes in a way not desired by the observer. In order to guard against this action, as is often necessary in long exposures, the photographic plates must be protected by suitable lead casings.

2. In order to compare the intensity of the radiation of two discharge-tubes, and for various other experiments, I have used an arrangement which is based on the principle of the Bouguer photometer, and which, for the sake of simplicity, I shall call a photometer also. A rectangular sheet of lead 35 centimetres high, 150 centimetres long, and 0.15 centimetre thick, supported on a board frame, is placed vertically in the middle of a long table. At each side of this is placed a discharge-tube, which can be moved along the table. At one end of the lead strip a fluorescent screen* is so placed that each half receives radiation perpendicularly from one tube only. In effecting the measurements, adjustments are made until there is equal brightness of the fluorescence on the two halves.

Some remarks on the use of this instrument may find a place here. It should be mentioned first that the settings are often made more difficult by the lack of constancy of the source of radiation, the tubes responding to every irregularity in the interruption of the primary current, such as occur with the

* In this and other experiments the Edison fluorescent screen has proved most useful. This consists of a box like a stereoscope which can be held light-tight against the head of the observer, and whose card-board end is covered with barium platino-cyanide. Edison uses tungstate of calcium in place of barium platino-cyanide; but I prefer the latter for many

Deprez interrupter, and especially with the Foucault instrument. Repeated settings are therefore advisable. In the second place, I should here enumerate the conditions which influence the brightness of a given fluorescent screen struck by X-rays in such rapid succession that the eye of the observer can no longer detect the intermittence of the radiation. This brightness depends (1) upon the intensity of the radiation which proceeds from the platinum plate of the discharge-tube; (2) very probably upon the kind of rays striking the screen, since all kinds of rays (see below) are not necessarily equally active in producing fluorescence; (3) upon the distance of the screen from the centre of emission of the rays; (4) upon the absorption which the rays experience on their way to the barium platino-cyanide screen; (5) upon the number of discharges per second; (6) upon the duration of each single discharge; (7) upon the duration and the strength of the after-illumination of the barium platino-cyanide; and (8) upon the radiation falling on the screen from the bodies which surround the discharge-tube. In order to avoid errors, it must always be remembered that the conditions are in general like those which would exist if we had to compare, by means of fluorescent action, two intermittent sources of light of different colors, which are surrounded by an absorbing envelope placed in a turbid—or fluorescing—medium.

3. According to paragraph 12 of my first communication, the point in the discharge-apparatus which is struck by the cathode rays is the centre of emission of the X-rays, and from this these rays spread out “in all directions.” It becomes now of interest to determine how the intensity of the radiation varies with the direction.

For this investigation the discharge-tubes best suited to the purpose are those in the shape of a sphere, with smoothly polished platinum plates, which are struck by the cathode rays at an angle of 45° . Even without further appliances we can recognize from the uniformly bright fluorescence of the hemispherical glass wall surrounding the platinum plate that very

exist; so that Lambert's law of emission does not hold in this case. Nevertheless, this fluorescence for the most part might still be due to the cathode rays.

To test this question more accurately, several tubes were examined by means of the photometer as to their radiation in different directions. Moreover, besides doing this, I have exposed with the same object photographic films bent into a semi-circle (radius 25 centimetres) about the platinum plate of the discharge-tube as a centre. In both experiments, however, the varying thickness of the different portions of the walls of the tube produced a disturbing action, because the X-rays, proceeding in different directions, were unequally absorbed. Yet by interposing thin plates of glass I finally succeeded in making the thickness of glass traversed about the same.

The result of these experiments is that the radiation through an imaginary hemisphere, described around the platinum plate as a centre, is nearly uniform almost out to the edge. It was not until the emission angle of the rays was about 80° that I noticed the beginning of a decrease in the radiation; and even then this decrease was relatively very small; so that the main change in the intensity occurs between 89° and 90° .

No difference in the kind of rays emitted at different angles have I been able to detect.

As a consequence of the distribution of intensity of the X-rays, as now described, the images of the platinum plate which are received—either on a fluorescent screen or on a photographic plate, through a pin-hole camera or with a narrow slit—must be more intense the greater the angle which the platinum plate makes with the screen or with the photographic plate; always presupposing that this angle does not exceed 80° . By means of suitable appliances which allow comparisons to be made between the images received simultaneously at different angles from the same discharge-tube, I have been able to confirm this conclusion.

A similar case of distribution of the intensity of emitted rays occurs in Optics in the case of fluorescence. If a few drops of

filled with water, and if at the same time we illuminate the tank with white or with violet light, we observe that the brightest fluorescence proceeds from the edges of the threads of the slowly sinking fluorescein—*i. e.*, from the places where the emission angle of the fluorescent light is the greatest. As Stokes has remarked, *à propos* of a similar experiment, this phenomenon is due to the fact that the rays which produce fluorescence are absorbed by the fluorescein solution much more strongly than is the fluorescent light itself. Now it is worthy of note that the cathode rays, which produce the X-rays, are absorbed by platinum much more than are the X-rays, and it is easy to conjecture from this that a relationship exists between the two phenomena—the transformation of ordinary light into fluorescent light, and that of cathode rays into X-rays. A conclusive proof, of any kind, of such an assumption is not known at the present time, however.

Moreover, with reference to the technique of the production of shadow pictures by means of X-rays, the observations on the distribution of intensity of the rays proceeding outward from the platinum plate have a certain importance. According to what has been stated above, it is advisable to place the discharge-tube in such a position that the rays used in producing the image shall leave the platinum plate at as great an angle as possible, though this should not be much over 80° . By this means the sharpest pictures are produced; and, if the platinum plate be perfectly plane, and the construction of the tube of such a kind that the oblique rays pass through a not materially thicker glass wall than those rays which are emitted perpendicular to the platinum plate, then the radiation on the object suffers no loss in intensity.

4. I have designated in my first communication by “transparency of a body” the ratio of the brightness of a fluorescent screen placed perpendicular to the rays, and close behind the body, to that which the screen shows when viewed under the same conditions, but with the body removed. “Specific trans-

d th root of the transparency, if d is the thickness of the layer traversed, measured in the direction of the rays.

In order to determine the transparency, I have used principally, since my first communication, the photometer described above. The body to be investigated—aluminium, tin-foil, glass, etc., made in the form of a plate—was placed before one of the two equally bright fluorescent halves of the screen; and the inequality in brightness thus produced was made to vanish, either by increasing the distance of the radiating discharge-apparatus from the uncovered half of the screen, or by bringing the other tube nearer. In both cases the correctly measured ratio of the squares of the distances of the platinum plates of the discharge-tubes from the screen, before and after the displacement of the apparatus, is the desired value of the transparency of the interposed body. Both methods led to the same result. By the addition of a second plate to the first, the transparency of the second plate may be found in a similar manner for rays which have already passed through one.

The method above described presupposes that the brightness of a fluorescent screen varies inversely as the square of its distance from the source of rays, and this is true, in the first place, only if the air neither absorbs nor emits X-rays, and if, secondly, the brightness of the fluorescent light is proportional to the intensity of emission of rays of the same kind. The first condition is certainly not satisfied, and it is doubtful whether the second is; I convinced myself long ago by experiment, as already described in paragraph 10 of my first communication, that the deviations from the law of proportionality are so small that they can be safely neglected in the case before us. It should be mentioned with reference to the fact that X-rays also proceed from the irradiated body, first, that a difference in the transparency of a plate of aluminium 0.925 millimetre thick, and of 31 aluminium sheets laid upon one another, each of a thickness of 0.0299 millimetre— $31 \times 0.0299 = 0.927$ —could not be detected with the photometer used; and, second, that the brightness of the fluorescent

front of the screen and when it was placed at a greater distance from it.

For aluminium, the results of this experiment on transparency are as follows :

TRANSPARENCY FOR PERPENDICULAR RAYS

	TUBE 2	TUBE 3	TUBE 4	TUBE 2
The first 1 mm. thick Al. plate	0.40	0.45	.	0.68
The second 1 mm. " " "	0.55	0.68	.	0.73
The first 2 mm. " " "	—	0.30	0.39	0.50
The second 2 mm. " " "	—	0.39	0.54	0.63

From these experiments, and from similar ones on glass and tin-foil, we deduce at once the following result : if we imagine a substance divided into layers of equal thickness, placed perpendicular to parallel rays, each of these layers is more transparent for the transmitted rays than the one before it ; or, in other words, the specific transparency of a substance increases with its thickness.

This result is completely in accord with what may be observed in the photograph of a tin-foil scale as described in paragraph 4 of my first communication ; and also with the fact that in photographic pictures the shadow of thin sheets—*e. g.*, of the paper used to wrap up the plate—is proportionally strongly marked.

5. Even if two plates of different substances are equally transparent, this equality may not persist when the thickness of the plates is changed in the same ratio, nothing else being altered. This fact may be proved most easily by the help of two scales placed side by side ; for instance, one of platinum, the other of aluminium. I used for this purpose platinum-foil 0.0026 millimetre thick, and aluminium-foil 0.0299 millimetre thick. I brought the double scale before the fluorescent screen, or before a photographic plate, and allowed rays to fall upon it ; I found in one case that a single sheet of plat-

equal not to that of a twelve-fold layer of aluminium, but to a sixteen-fold layer. Using another discharge-tube, I obtained, 1 platinum = 8 aluminium ; 8 platinum = 90 aluminium. It follows from these experiments, therefore, that the ratio of the thickness of platinum and aluminium of equal transparency is smaller in proportion as the layers in question become thicker.

6. The ratio of the thicknesses of two equally transparent plates of different materials depends also upon the thickness and the material of the body—*e. g.*, the glass wall of the discharge-apparatus—which the rays must first traverse before they reach the plates in question.

In order to prove this conclusion—which is not surprising after what has been said in sections 4 and 5—we may use an arrangement which I call a platinum-aluminium window, and which, as we shall see, may also be used for other purposes. This consists of a rectangular piece (4.0×6.5 centimetres) of platinum-foil of 0.0026 millimetre thickness, which is cemented to a thin paper screen, and through which are punched 15 round holes, arranged in three rows, each hole having a diameter of 0.7 centimetre. These little windows are covered with panes of aluminium, 0.0299 millimetre thick, which fit exactly, and are carefully superposed in such a way that at the first window there is one disk ; at the second, two, etc. ; finally, at the fifteenth, fifteen disks. If this arrangement be brought in front of the fluorescent screen, it may be observed very plainly, in case the tubes are not too hard (see below), how many aluminium sheets have the same transparency as the platinum-foil. This number will be called the window-number.

For the window-number I obtained in one case by *direct* radiation the value 5. A plate of common soda-glass, 2 millimetres thick, was then held in front ; the window-number was 10. So that the ratio of the thickness of the platinum and aluminium sheets of equal transparency was reduced one-half when I used rays which had passed through a plate of glass 2 millimetres thick instead of using those coming direct from the discharge-apparatus. Q. E. D.

phase: The platinum-aluminium window was laid upon a small package which contained 12 photographic films, and was then exposed; after development, the first film lying under the window showed the window-number 10, the twelfth the number 13; and the others, in proper order, the transition from 10 to 13.

7. The experiments communicated in sections 4, 5, and 6 refer to the modifications which the X-rays coming from a discharge-tube experience on passing through different substances. It will now be proved that one and the same substance, with the same thickness traversed, may be transparent in different degrees to rays which are emitted by different tubes.

In the following table are given, for this purpose, the values of the transparency of an aluminium plate 2 millimetres thick for rays produced in different tubes. Some of these values are taken from the first table on page 28:

TRANSPARENCY FOR PERPENDICULAR RADIATION						
TUBES						
	1	2	3	4	2	5
of an Al. plate 2 mm. thick,	0.0044	0.22	0.30	0.39	0.50	0.59

The discharge-tubes are not materially different in their construction or in the thickness of their glass walls, but vary mainly in the degree of exhaustion of the contained gas and in the discharge-potential which is conditioned by this; tube 1 requires the lowest, tube 5 the highest, potential; or, as we shall say, to be brief, tube 1 is the "softest," tube 5 the "hardest." The same induction-coil—in direct connection with the tubes—the same interrupter, and the same strength of current in the primary were used in all the cases.

All the many other bodies which I have investigated behave in the same manner as aluminium; all are more transparent for the rays of a harder tube than for those of a softer one.* This fact seems to me to be worthy of special consideration.

* See below for the behavior of "non-normal" tubes.

The ratio of the thicknesses of two equally transparent plates of different substances is also dependent upon the hardness of the tube used. This may be recognized immediately with the platinum-aluminium window (§ 5); with a very soft tube, for example, the window-number may be found to be 2; while with a tube which is very hard, but otherwise the same, the scale which reaches No. 15 does not extend far enough. This means, then, that the ratio of the thicknesses of platinum and aluminium of equal transparency is smaller in proportion as the tubes from which the rays come are harder, or—with reference to the result reported above—as the rays are less easily absorbed.

The different behavior of rays produced in tubes of different hardness is self-evident also in the familiar shadow-pictures of hands, etc. With a very soft tube, dark pictures are obtained in which the bones are not very prominent; by using a harder tube the bones are very plain and all the details are visible, the soft parts, on the contrary, being weak; while with an extremely hard tube only faint shadows are obtained, even of the bones. From what has been said it follows that the choice of the tube to be used must depend upon the constitution of the object to be pictured.

8. It still remains to note that the quality of the rays furnished by one and the same tube depends upon a variety of conditions. As the investigation made with the platinum-aluminium window shows, this is influenced: (1) By the manner and perfection with which the Deprez or Foucault interrupter* works—*i. e.*, by the variation of the primary current; to this belongs the phenomenon so often observed, that single discharges out of a rapid succession produce X-rays which are not only particularly intense, but which are distinguished from the others by the [*slight*] extent to which they are absorbed; (2) by a spark-gap which is included in the secondary circuit of the discharge-apparatus; (3) by including in the circuit a Tesla

* A good Deprez interrupter works more regularly than a Foucault apparatus; the latter, however, utilizes the primary current better.